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Study of the energy potential of the biogas produced by an urban waste landfill in Southern Spain

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Abstract

Sanitary landfills have been and continue to be one of the most common ways to dispose of urban waste although such landfills inevitably generate waste management problems. Landfills are an important source of anthropogenic CH_4 emissions. In this sense the European Union has passed regulations regarding the effective management of biogas within the framework of an EU policy for renewable energies. The sealed landfill analyzed in this study is an example of energy recovery, but in this case the biogas generated by the landfill is being re-used to produce electrical energy. This article presents the results of the economic viability study, which was carried out previous to the construction of the installation. The results based on the use of empirical and theoretical models show the biogas to have a 45% proportion of methane and an overall flowrate ranging from 250 to 550 N m^3/h. It is presently being used to produce electricity amounting to approximately 4,500, 000 kW h/year. The economic viability of the installation was estimated by means of the Internal Recovery Rate (IRR) for an exploitation period of 7 years.

Keywords: Landfill gas; Energy recovery; Renewable energy; Economic analysis

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1. Introduction

1.1. Environmental impacts of landfill gas

Waste disposal in landfills can generate environmental problems such as water pollution, unpleasant odors, explosion and combustion, asphyxiation, vegetation damage, and greenhouse gas emissions [1–3]. Different methods are presently being used to evaluate these problems in order to find solutions for them [4–7].

Landfill gas (LFG) is a naturally occurring by-product of the decomposition of organic waste in sanitary landfills, and is produced during the microbially mediated degradation of the organic portion of waste. An example of the conversion of a biomass into usable energy can be seen in sanitary landfills that produce an amount of biogas of about $0.350\,N\,m^3/kg$ of solid urban waste [8,9].

Landfill gas is generated under both aerobic and anaerobic conditions. Aerobic conditions occur immediately after waste disposal due to entrapped atmospheric air. The initial aerobic phase is short-lived and produces a gas mostly composed of carbon dioxide. Since oxygen is rapidly depleted, a long-term degradation continues under anaerobic conditions, thus producing a gas with a significant energy value that is typically 55% methane and 45% carbon dioxide with traces of a number of volatile organic compounds (VOC) [10–12]. Most of the CH_4 and CO_2 is generated within 20 years of landfill completion, whereas emissions may continue for 50 years or more.

There are two possible solutions for the problem of LFG emissions. One solution is the extraction and flaring of the LFG, a method often used in the past to reduce the pressure of

the LFG as well as its odor. The other solution is to reuse LFG for other purposes. Since its total chemical energy is sufficient to sustain the operation of a gas turbine, it is evidently a valuable energy resource. In fact, it can be used as a supplementary or primary fuel to increase the production of electric power, as a pipeline quality gas and vehicle fuel, or even as a supply of heat and carbon dioxide for greenhouses and various industrial processes [1,13].

The use of biogas as a fuel source is environmentally sound because it contributes to a reduction of fossil fuel use and mitigates the greenhouse effect. In particular, the emissions of CH_4, one of the two greenhouse gases emitted, are almost 21 times more dangerous than carbon dioxide for the greenhouse effect [8,14]. Landfills comprise the principal source of anthropogenic CH_4 emissions, and are estimated to account for 3–19% of anthropogenic CH_4 emissions globally [15]. The recovery of landfill gas for use as an energy resource is now an area of vital interest since it is a creative solution for both environmental pollution and energy shortage [16,17].

This article presents the results of a study of the energy potential of a sanitary landfill located in southern Spain (Granada) previous to the installation of internal combustion engines in the autumn of 2003.

1.2. Landfill gas as a renewable energy source

When the Kyoto Protocol and the Marrakech Agreement of 2001 go into effect, developing countries may have to significantly reduce greenhouse gas emissions in the coming decade. In a parallel way, they will also have to seek a way to minimize the socioeconomic impact of such a policy. The increased use and promotion of renewable energy technologies seem to be a viable solution [8,13,18].

In Spain the deployment of such energy technologies is regulated by strategic plans and laws such as the *Plan de Fomento de Energías Renovables*[1] (PLAFER) [19] and the *Real Decreto 2818/98* [20] regarding electricity production by installations using renewable energy sources, waste products, and co-generation.

The Andalusian regional government, as part of its environmental policy, has developed a series of strategic plans regarding the planning, organization, and coordination of action in this area. In 2000 the second *Plan Energético de Andalucía*[2] (2003–2006) [21] was implemented. This plan seeks to bring together all of the directives regarding energy initiatives that will be carried out in Andalusia during the stated time period. This plan is committed to environmental protection and targets the diversification of energy sources with a view to making use of the abundant renewable energy resources available in the region.

In 2000 energy consumption in Andalusia amounted to 11,569 ktep and within this same time period renewable energies accounted for 649 ktep. The contribution of biomass to the structure of energy consumption was 90% followed by hydraulic energy with 5.3% [21].

In Spain there have been various initiatives aimed at the recovery of biogas from urban waste landfills as shown in the following examples [22]: (i) Serín (Asturias) with waste deposits of 408,234 Tm/year and a nominal power of six engines at 750 kW, one engine at 300 kW, and two engines at 250 kW; (ii) Artigas (Bilbao) with waste deposits of 243,361 Tm/year and a nominal power of two engines at 450 kW; (iii) San Marcos

[1]Plan for the Promotion of Renewable Energies.

[2]Energy Development Plan for Andalusia.

(San Sebastian) with waste deposits of 146,172 Tm/year and a nominal power of two engines at 650 kW; (iv) Gungora (Pamplona) with waste deposits of 118,016 Tm/year of waste and a nominal power of one engine at 750 kW. This information is eloquent proof that biomass is a significant source of renewable energy. An example of the conversion of a biomass into usable energy can be seen in sanitary landfills.

1.3. Legal questions

Although in Spain there is no legislation that specifically regulates the efficient management of biogas in controlled deposits of urban waste, the European Union has published recommendations and enacted directives that have already begun to significantly affect Spain.

1.3.1. Directive 96/61/CE regarding the integrated prevention and control of pollution

Incorporated into Spanish legislation as *Ley 16/2002*, Directive 96/61/CE was passed to prevent and reduce the contamination of the atmosphere, water, and soil produced by industrial activity, and includes the treatment and elimination of urban waste. Salient aspects of this directive are the following [23]: (i) Member States of the European Union must take the necessary measures to provide that the competent authorities ensure that installations are operated in such a way that all the appropriate preventive measures are taken against pollution, in particular through application of the best available techniques; (ii) Energy must be used efficiently, and necessary measures taken to prevent serious accidents and limit possible negative impacts; (iii) When an industrial installation is closed down and ceases operation, necessary measures must be taken upon definitive cessation of activities to avoid any pollution risk and return the site of operation to a satisfactory state (post-closure responsibility).

1.3.2. Directive 99/31/CE on landfilling of waste

After various proposals, drafts, and discussions to find common ground on environmental protection, Directive 99/31/CE (*Real Decreto 1481/2001* in the Spanish legal code) was enacted and passed. It contains the following regulations regarding the management of gases [24]: (i) Appropriate measures will be taken to control the accumulation and emission of landfill gas; (ii) At all landfills where biodegradable wastes are deposited, gas will be recovered, treated and recycled. If the gas obtained cannot be used to produce energy, it should be burnt; (iii) The storage, treatment, and reuse of landfill gas will be carried out in such a way as to avoid, insofar as possible, negative impacts on the environment and public health; (iv) Gas should be monitored at each section of the landfill. In those landfills in which gas cannot be reused to create energy, it will be monitored at the site where such gas is emitted or burnt.

1.3.3. Resolution 97/C76/01 on an EU waste management strategy

Resolution 97/C76/01 was passed on February 24, 1997. In Article 35 it specifically affirms that members of the European Union should take the necessary cleanup measures to guarantee the restoration of former landfill sites and other contaminated locations to a satisfactory state [25].

1.3.4. COM(96)557. Communication regarding a strategy for the reduction of methane emissions

In order to take into account the potential effect of methane emissions on the climate, this communication points out the need to analyze the problems derived from such emissions as well as the need to identify sources and drainage sites. It also underlines the necessity of establishing a common strategy. This would basically consist of methods of reducing emissions as well as a set of guidelines in this regard that would be incorporated into the legislation of Member States.

Among the measures to be implemented would be the establishment of an objective for the reduction of emissions to be achieved in a given time period. The political measures established would be evaluated according to their cost–benefit in terms of potential economic and social consequences.

According to a previous study, the main focus should be on those sectors that make the largest contributions to methane emissions, notably agriculture, waste and energy which in 1990 accounted for 45, 32 and 23% of EU methane emissions, respectively.

The main source of the methane emissions derived from waste management is the anaerobic fermentation of the organic material deposited in landfills. Communication COM(96)557 includes the following recommendations [26]: (i) A distinction should be made between existing landfills and new landfills; (ii) In the case of existing landfills, authorities should improve their technological capacity and environmental level by incorporating the infrastructure necessary for the management of methane emissions; (iii) In the case of new landfills, the permits granted to controlled anaerobic deposits should be strictly monitored. In any case, it is always necessary to verify whether there are other ways of limiting methane emission, and at the same time incorporate highly efficient systems for its reception and energy evaluation; (iv) When such evaluation is not feasible, the infrastructure necessary for its total combustion should be available and operative; (v) Finally, Member States should develop economic incentives to favor the recovery of methane gas, the use of technologies, and the reduction of the amount of organic matter deposited in landfills.

Decision 99/296/CE published on April 26, 1999, modified Decision 93/389/CEE regarding the monitoring of CO_2 and other greenhouse gases such as methane. This decision affirms that Member States should make an inventory of the sources of gas emissions and their elimination by drainage sites, as well as describe the policies and national regulations adopted to reduce such emissions, and thus facilitate their total elimination.

As can be observed, these regulations are somewhat ambiguous in reference to the measures to be taken for the efficient management of biogas. Nevertheless, what is clear is the message regarding the need to reduce and minimize the negative impact that uncontrolled biogas emission has on the environment.

2. An urban waste landfill in Granada (Spain)

2.1. Profile of the landfill

The landfill studied in this article is located 2 km northeast of Granada, a city in southern Spain with a population of 300,000 inhabitants. The landfill, with a surface area of 46.54 Has, was in active operation from 1984 to 1999. During this period, the waste was

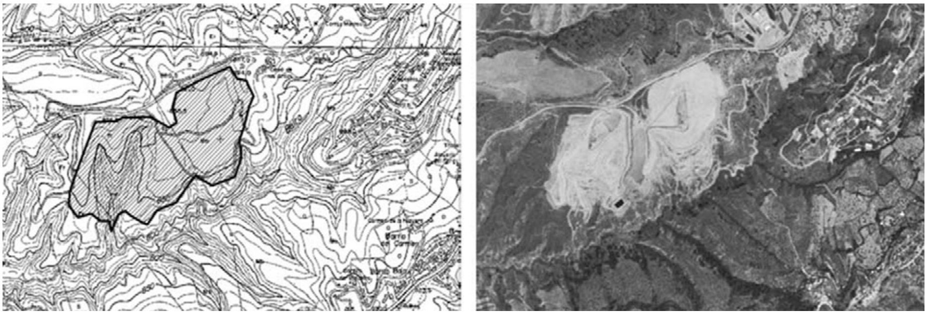

Fig. 1. Location of the landfill (Granada, Spain).

deposited on a hillside running along the river Beiro with an average altitude of 870 and 500 m (see Fig. 1).

The landfill is of medium density, and over the years was progressively covered with layers of soil from the same area and similar to that found in the bed of the landfill. The waste compacting process was carried out by means of compacting equipment, with a waste compacting degree of 0.7–0.9 Tm/m^3. The leachate was collected in pools where it was pumped out again to be recirculated in the landfill. The extraction of the gas was carried out by a series of gas extraction wells separated by distances of 30–35 m.

In 1999 with a view to mitigating the negative environmental impact, the landfill was sealed. Subsequently, plans were drawn up to construct installations to extract biogas and reuse it to create electrical energy. The project was carried out that same year by INAGRA (company belonging to CESPA[3]).

The average annual precipitation in this region fluctuates from 66 to 400 mm during the seasons of autumn and winter. The average annual temperature in Granada largely depends on the weather station where the measurements are obtained. The average temperature is 15.3 °C as measured at the Cartuja weather station in the city, whereas it is 14.8° at the airport weather station, 10 km outside the city.

The temperature in Granada is influenced by the proximity of the Sierra Nevada mountain range. The highest temperatures occur during the summer months, while the lowest ones occur in December and January. The thermal variation in the average annual temperatures is significant, and amounts to almost 20 °C. This is the same variation that exists between daytime and nighttime temperatures.

The potential evapotranspiration of the area, as calculated by the Thornthwaite Method, reaches values ranging from 700 to 900 mm. There is generally a period of draught in the summer months.

The landfill is located on the Alhambra formation, made up of conglomerates and sands, immersed in a large clayey basin, reducing the capacity of water transmission in the subsoil. There are no aquifers or signs of surface or groundwater at the landfill site.

After the landfill was sealed, urban waste from Granada, as well as that from other neighboring cities and towns, was treated at the *Planta de Recuperación y Compostaje*, a waste recovery and composting installation that had recently opened in the town of Alhendin, 20 km outside of Granada. The main products treated at this plant are: metals,

[3] *Cespa* is a consortium of businesses offering a wide range of waste management services.

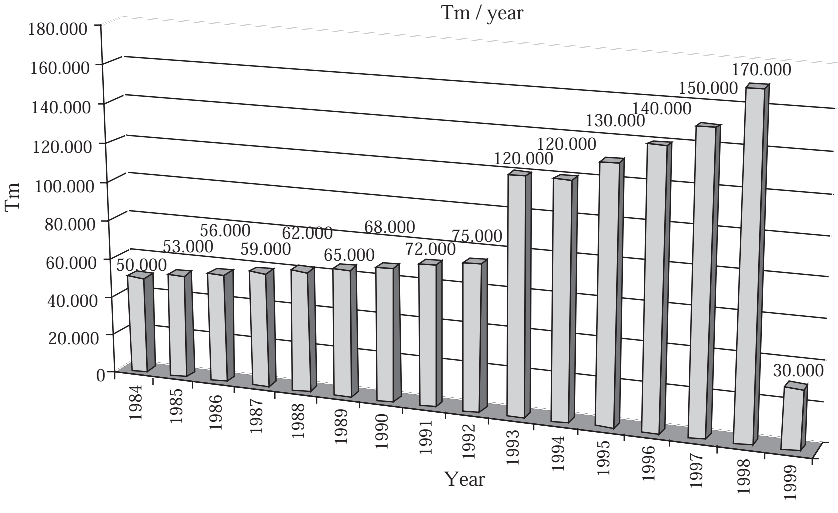

Fig. 2. Quantity of waste deposited annually at the landfill.

paper and cardboard, plastics and containers of mixed composition, organic material for the elaboration of compost, other wastes.

2.2. *Production and characterization of wastes*

During its period of maximum activity, a total of 1,420,000 Tm of waste were deposited at the landfill. A clear increase of waste production can be observed in Fig. 2, which shows the amount of waste deposited at the landfill from 1984 to 1999. This is typical of tendencies in recent decades and in consonance with the average rate of waste generation [18,27].

The waste was analyzed in order to obtain its macroscopic composition. The results of the field study is appear in Table 1.

2.3. *Quantification of the theoretical production/yield of biogas*

A number of methods have been used to estimate CH_4 emissions at waste disposal sites. These methods vary greatly, not only in their assumptions, but also in their complexity and in the amount of data required. Some are based on the theoretical gas yield, whereas others use a first-order kinetics equation [28–32].

2.3.1. *Empirical estimate of biogas*

The estimate of biogas production has been carried out by means of empirical calculation, in other words, a calculation using both experimental and theoretical data. Based on the macroscopic characteristics of the waste and the degradability data given in the previous section, as well as the analysis of the sample of gas spontaneously emitted from the landfill, it was possible to postulate the chemical formula of the waste (see Table 2).

Table 1
Macroscopic composition of the landfill waste

Macroscopic composition of waste	Weight (%)	Humidity (%)	Weight of dry waste (%)	Degradability of dry waste (%)		
				Fast	Slow	Total
Organic waste	30.50	75.00	7.63	75.00	7.00	82.00
Wet Paper/Cardboard	24.00	20.00	19.20	30.00	20.00	50.00
Wood/Garden trimmings	1.50	35.00	0.98	10.00	20.00	30.00
Textiles	1.00	20.00	0.80	0.00	10.00	10.00
Plastic	21.00	1.00	20.79	0.00	0.00	0.00
Metals	5.00	1.00	4.95	0.00	0.00	0.00
Glass	12.00	1.00	11.88	0.00	0.00	0.00
Others and inert matter	5.00	1.00	4.95	5.00	16.00	21.00
Total	100.00	28.83	71.17	11.82	5.44	17.26

Table 2
Estimated chemical formula of waste

Dry fraction	Degradables	Chemical formula
71.17%	17.26%	$C_{44}H_{70}O_{29}N$

Table 3
Estimated biogas production and methane concentration

Methane production (m^3/Tm)	Biogas production (m^3/Tm)	Methane concentration (% v/v)
82.43	160.21	51.39

The amount of biogas produced per ton of waste has been defined by the decomposition equation. The results obtained for a 40-year decomposition period are summarized in Table 3.

2.3.2. Theoretical and actual production of biogas

The previous section presents the possible generation of biogas per ton of waste, the composition of which was calculated hypothetically. It is a stoichiometric calculation on the basis of hypothetical data, but reality inside an actual landfill is much more complex. Another element of great importance in the evaluation of potential landfill gas production is the kinetics of decomposition. Some researchers use models or algorithms based on equations that presuppose the exact knowledge of waste composition [23]; others use models based on experiments carried out in a controlled environment [33]; and others based on their research on field measurements [29].

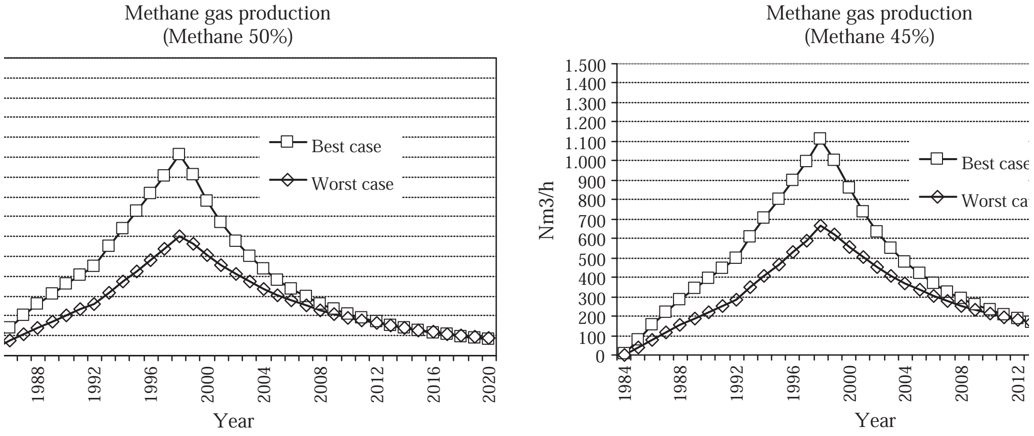

Fig. 3. Best and worst case scenarios with methane gas production.

In this case a mixed theoretical–practical method was used for the determination of the kinetic model developed by Tabasaran (1976) [30] with subsequent modifications such as Weber's (1996) [31]. This method permits the construction of a 'normal' productivity curve for each ton of waste within the context of two different scenarios: (i) a best case scenario based on optimum local conditions for gas production and extraction with a percentage of organic material for rapidly decomposing waste (RDW) of 34% and one of organic material for slowly decomposing waste (SDW) of 23%; (ii) a worst case scenario, in which local circumstances are not as positive as the current interpretation of available data with a percentage of organic material for RDW of 31% and a percentage of organic material for SDW of 21%.

Given the contrast between these two scenarios, each evaluation has been carried out with a different set of parameters. In this way production levels are obtained that vary from 172.43 m^3/Tm in the most unfavorable case to 115.92 m^3/Tm in the most favorable one. The theoretical estimate of 160.21 m^3/Tm, which was calculated on the basis of hypothetical waste composition, falls within this range.

Nevertheless, there are more complex reactions that take place inside the landfill, and which produce other compounds such as H_2S, mercaptans, CO, water vapor, N_2 and O_2. Moreover, depending on the exploitation system of the landfill and its energy recovery system [34], it may also be necessary to apply a methane correction factor (MCF) such that the final proportion of methane is estimated at 45%, a percentage similar to that obtained in other research [8,18,35].

Fig. 3 represents both the best and worst case scenarios, and shows production curves for methane gas concentrations of 50 and 45%, respectively.

Since what most interests us is the production that is actually available as well as the most probable concentration, the estimates here correspond to a production in which there is a 45% methane concentration. Given this concentration and the fact that the biogas produced inside the landfill is a combustible gas with a low calorific value (LCV) of approximately 4000 kcal/N m^3 (depending on its methane content), the case under study shows an LCV of 3861 kcal/N m^3. This means that the biogas has a high energy content, and thus can be used to produce electrical energy [14].

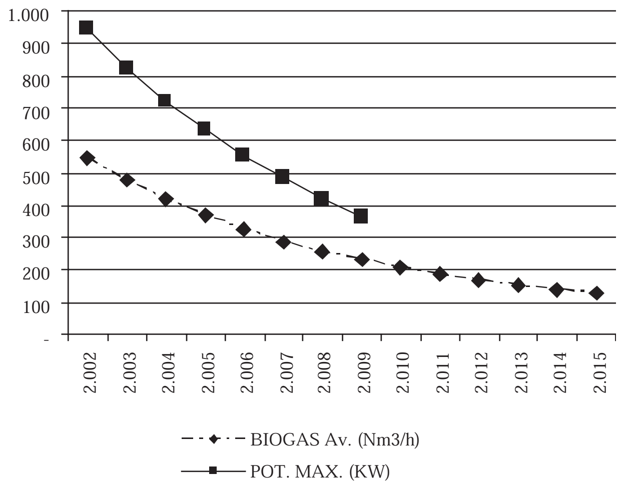

Fig. 4. Available biogas and maximum exploitation potential during 2002–2010.

Fig. 4 shows the biogas available for a period of exploitation associated with a maximum exploitation potential. The useful life of the project depends on the useful life of the engine/turbine, which is generally around 7.5 years (operating 8000 h/year) or 8 years (operating 7500 h/year). The installation will continue to burn biogas with a high-temperature flare to guarantee a healthy environment. Since the replacement or large-scale repair of the engine/turbine at the end of its useful life would signify an excessively large investment for the low volume of biogas expected after this date, it is not considered to be economically viable.

The sealed landfill in Granada can be regarded as a landfill with a relatively high biogas yield, estimated at 250–550 N m^3/h. This permits an average production of electrical energy of 4,500,000 kW h/year. For this reason, it is necessary to have an active gas collection system as well as an elimination system through controlled combustion that generates electricity. In order to obtain optimal biogas management, the best alternative was to centralize the degasification of the landfill in one place. The following sections describe the infrastructure employed to degasify the landfill and outlines aspects of the energy recovery system.

3. Installation design

The technology proposed for the extraction and reuse of biogas can be regarded as standard technology. It is the most up-to-date technology in full compliance with both EU and Spanish legislation. The design chosen for the gas extraction and utilization system is the type generally used for such installations. The calculation of the total cost is based on this design. The following section briefly describes the components of the installation.

3.1. Collection and extraction system

The gas collection system includes a network of 50 vertical gas extraction wells, as seen in Fig. 5, dewatering units, HDPE gas transport pipelines, and a flare. The control

Fig. 5. The gas collection system.

activities for this system consist of periodic adjusting of the gas wells by means of monitoring equipment. The gas extraction plant is equipped with blowers, which create a suction pressure in the system necessary for extraction of the LFG. Removal and reconstruction of the gas extraction system elements is essential to maintain high gas yields.

3.2. Energy recovery system

Desgasification equipment, such as flares, pipelines and blowers, was gauged according to the most optimistic gas production curve since it is necessary to assure the total environmental recovery of the landfill site. However, for electricity generation, it is necessary to study (i.e. in terms of best and worst case scenarios) which is best type of generator for such an installation. It is thus necessary to take into account that the plant will be operating 8000 h/year over a period of 7.5 years (60,000 h), and that the flow volume of the biogas should not ever be lower than 50% of the maximum design flow of the engine.

For example, the study showed that an engine of 836 kW would only be viable for the best case scenario. In contrast, however, it was found that an electrical engine of 624 kW would be able to operate for 60,000 h without ever falling below 50% of the design flow in

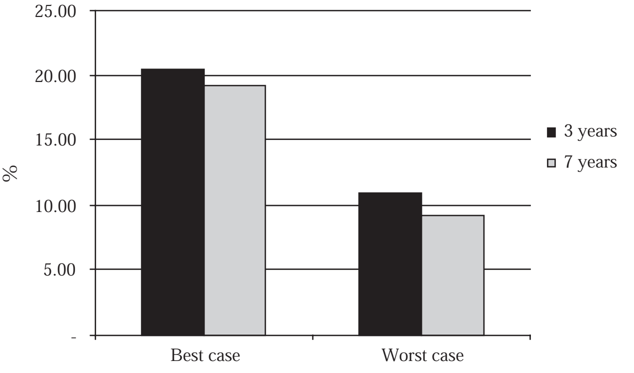

Fig. 6. Internal Recovery Rate for 3- and 7-year exploitation periods.

either the best or the worst case scenario for biogas generation, and so this was the type of engine chosen.

4. Economic viability

The economic viability of landfill gas (LFG) utilization depends on a number of factors, including LFG quality, local energy prices (electricity, steam, gas or other derived products), and choice of equipment. The specification of economic criteria for LFG electricity generation technology is based on cost–profit analysis. The cost is divided into capital costs, annual operation and maintenance (O&M) costs, as well as coal tax and energy tax, which can be added to vital factors for quality environmental protection. The profit is the sales revenue from electricity generation [14].

In the calculation of the profitability of the project, both best case and worst case scenarios were taken into account, as well as the cost of amortization and exploitation. The economic viability of the landfill was determined by an economic study based on Cash Flow, using the profitability parameter of the Internal Recovery Rate (IRR) for a period of 3 years and another period of 7 years.

In the context of these economic profitability hypotheses for the best and worst case scenarios (see Fig. 6), there are no significant differences in the IRR. This means that the landfill can be satisfactorily and profitably exploited for 7 years from both an economic and an environmental perspective.

5. Conclusions

Both empirical and theoretical design models have estimated a 45% methane concentration in the volume of the biogas generated with an LCV of 3861 kcal/N m^3.

The analysis of the biogas produced at the landfill shows that the overall flowrate ranges from 250 to 550 N m^3/h, which signifies a potential average electricity production of 4,500,000 kW h/year. On the basis of such data, the economic viability of the installation for biogas recovery was estimated to have an IRR of 20% for an exploitation period of 7 years.

The results obtained show that the recovery of biogas at the sealed landfill in Granada is a highly desirable alternative in urban waste management. Furthermore, the use of biogas as a fuel source is environmentally sound because it increases the use of renewable energy sources and reduces the greenhouse effect of methane and the carbon dioxide emissions.

The results of the first year of operation of this installation have recently been obtained. This will allow us to validate the results presented in this article and will give rise to future publications.

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